# THE APPLICATION OF HIGH-RESOLUTION LASER ALTIMETRY TO DEGLACIATION DYNAMICS: ANNAPOLIS ROYAL, NOVA SCOTIA

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## ABSTRACT

Light detection and ranging (LiDAR) was used to examine meso-scale (dam - km) glacial landforms on North Mountain and the Annapolis Valley of Nova Scotia. Meso-scale glacial landforms are difficult to identify under forest cover using traditional methods, but record important glacial dynamics information. High resolution, "bald Earth", digital elevation models (DEM's) produced from LiDAR data were used to identify surficial and glacial landforms that were not detected with previous mapping methods. An esker system north of Annapolis Royal and drumlinoids in the Annapolis Valley support previously controversial interpretations of northwestward ice flow across North Mountain towards the Bay of Fundy. Numerous wave-cut terraces which have truncated the lower elevations of the esker system north of Annapolis Royal during late glacial sea-level transgression (12-14 ka) are mappable from the high resolution DEM's. The morphosequence concept has been formally applied for the first time in Nova Scotia, based on the meso-scale glacial landforms in the project area. A previously unidentified esker system was discovered south of Annapolis Royal. These esker systems are a source of aggregate for the construction industry (the new system contains >750 x $10^3$ T of potentially economically viable aggregate).

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## Acknowledgements

This project would not have been possible without the support and mentoring of Tim Webster (AGRG/NSCC) and John Gosse (DAL) who have spent many hours of their personal time assisting me during the project. I thank COGS and AGRG for the use of their computers, data and processing help. I appreciate the help and input from both Ralph Stea (formerly NSDNR) and Andrée Bolduc (GSC) whose ideas and previous work much of this project is built around. I would like to acknowledge Gordon Dickie and Jeff Newton at Shaw Resources who have allowed me the time without question and financial support to work on this project. Special thanks to Pat Ryall and the honours class students for all the help throughout this year.

# CHAPTER 1 INTRODUCTION

## 1.1 Purpose

Advances in technology are allowing Quaternary and surficial geologists to use higher resolution imagery to visualize landscapes (Liverman et al., 2006), and reinterpret deglaciation ice dynamics (Kleman et al., 2006). Previous ice dynamics histories are based on field work where striae and related mm-cm scale landforms provide ice flow directions and relative ages. Stratigraphy can provide flow history from provenance analysis and can also provide numerical and relative chronology of flow events. Aerial photos and topographic maps can be used to interpret mostly kilometer-scale landforms to help support the more detailed field work. There is an ongoing trend to incorporate meso-scale (dam-km) landforms into ice dynamics models (Kleman et al., 2006, Liverman et al., 2006). In this project, light detection and ranging (LiDAR) is used to examine meso-scale glacial landforms on North Mountain and the Annapolis Valley of Nova Scotia. Meso-scale glacial landforms are difficult to identify under forest cover using traditional methods (field work, aerial photos, radar and satellite imagery), but may hold clues to the deglaciation dynamics of the region. LiDAR data provides the resolution to yield significant improvements in surficial maps due to the ability to detect subtle glacial landforms which greatly enhances the understanding of deglaciation. Glacial landforms were identified with the use of LiDAR imagery that have not been identified in previous surficial mapping campaigns. The new information has implications on published interpretations of ice dynamics in the area.

The purpose of this study is to provide proof that 'bald Earth' LiDAR imagery has the resolution required to generate data for mapping meso-scale landforms. Landforms in the study area that had never been previously mapped (confirmed by A. Bolduc, personal communication 2007, and R.R. Stea, personal communication, 2007) are also identified in the study. The project will evaluate a contested, but previously untested, hypothesis regarding the proposed northwestward ice flow from Nova Scotia into the Fundy Basin that was not affected by the deep Annapolis Valley (Stea et al., 1998, Shaw et al., 2006). Newly identified landforms that are potential aggregate sources are studied to determine the total sand resource and current market value. This project will also be the first time that the morphosequence concept has been applied to landforms in Nova Scotia.

## 1.2 Significance

The study of glacial landforms utilizing LiDAR is significant because very little research on the subject of deglaciation has been completed with the aid of LiDAR. The imagery available with LiDAR enables unidentified landforms to be discovered and documented with decimeter precision. LiDAR technology has been extensively used in geological mapping (Webster et al., 2006) as well as in predicting storm surge flood risk (Webster and Forbes et al., 2006), landslide hazard areas (Haugerud et al., 2003) and forest cover (Zimble et al., 2003), but detailed examination of glacial geology has been limited. Since World War II surficial geology in remote areas of Canada has been mapped using aerial photography at scales of 1:60,000 to 1:20,000. Satellite imagery allowed larger scale (km) landforms to be identified but was still limited to relatively low resolution until radar became available in the 1980's. Liverman (2006) has used Shuttle Radar Topography Mission (SRTM) data to identify large scale landforms in Newfoundland but this data still lacks the resolution of LiDAR derived DEM's and does not penetrate the vegetation canopy. The study area has a landscape that has developed over millions of years with many episodes of glaciation that have overprinted the terrain with both large and very subtle glacial features (Webster et al., 2006) complicating surficial mapping. The application of LiDAR to surficial geomorphology allows a detailed view of landforms that may have previously been undetected. Forest cover greatly diminishes the ability of an observer to identify glacial deposits from aerial photography when compared to the detail provided by 'bald Earth' DEM's developed from LiDAR (Webster et al., 2006). The ability to plan LiDAR missions during leaf-off conditions in the spring and fall, and the ability of the laser to penetrate the canopy allows new and complete views of previously obscure landscapes. Images created from LiDAR can even aid in piecing together deposits that were eroded, mined for aggregate use or dissected by other anthropogenic influence. Identifying meso-scale landforms are necessary for morphosequence interpretation and are readily visible on LiDAR imagery.

# CHAPTER 2 BACKGROUND

## 2.1 Physiography and Geology of North Mountain and Annapolis Valley

### 2.1.1 Physiography

The North Mountain is located in western Nova Scotia on the southeastern shores of the Bay of Fundy. The study area is located in the southwestern region of the North Mountain to the east of Annapolis Royal (Fig. 2.0). The North Mountain is bounded by Brier Island in the southwest, Cape Blomidon in the northeast and lies between the Bay of Fundy to the north and the Annapolis Valley to the south. The Annapolis Valley is dissected by the southward flowing Annapolis River which empties into the Bay of Fundy.

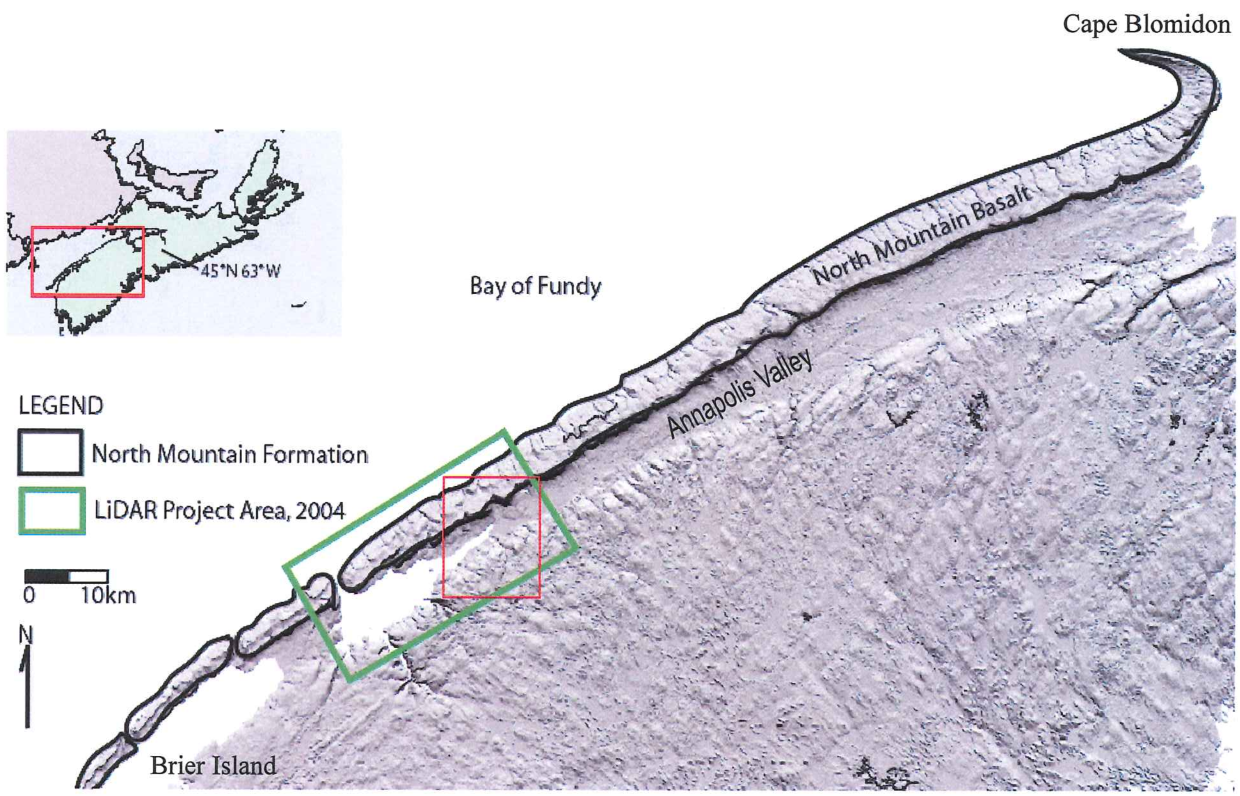



**Figure 2.0 April 2004 LiDAR Survey Area** (after NS Department of Natural Resources, 2004), red area indicates project study area.

The area has varying relief, which to a large extent is controlled by the regional bedrock. At the kilometer and larger scale, topography ranges from sea level at the Bay of Fundy to 265 m asl on the North Mountain. Gradients towards the Bay of Fundy average 3°-5° from the crest of the North Mountain. At finer scales, the coastline exhibits complex topography with gentle beaches and bedrock platforms to 25 m cliffs and embayments (Webster et al., 2006). The North Mountain is in the Acadian Vegetation Region whose main tree species include Red Spruce, Balsam Fir, Maple, Spruce, Yellow Birch, Red Pine and White Pine (Stanford, 2003). The western areas have more extensive forest cover than eastern areas which have an abundance of farms and pastures, depending on till cover thickness (Webster et al., 2006).

The region has a modified continental climate (Webster et al., 2006) that is controlled by the nearby Bay of Fundy and the Atlantic Ocean. Sea ice does not form during winter months allowing the relatively warm sea surface temperatures to moderate the winter temperatures (Stanford, 2003). The area sees on average 1.0 m of rain and 0.2 m of snow on an annual basis, based on data collected between 1971 and 2000 (Environment Canada, 2004). Based on well preserved landforms in the area, neither paleoclimate nor current conditions have had a significant influence on the preservation of surficial landforms.

### 2.1.2 Surficial and Bedrock Geology

The North Mountain consists almost entirely of Jurassic basalt (North Mountain Formation) referred to as the North Mountain Basalt (NMB) (Fig. 2.0). The NMB is the northernmost extent of the Central Atlantic Magmatic Province that is characterized by basaltic magmatism erupted during the beginning stages of the opening of the Atlantic Ocean. Three different flow units comprise the NMB differentiated by physical and chemical characteristics (Webster et al., 2006). The NMB gently dips to the northwest and forms the southeast limb of a regional syncline (Withjack et al., 1995). The lower flow unit (LFU) is approximately 40-150 m thick and consists of one massive, columnar jointed flow. The middle flow unit (MFU) lies conformably over the LFU and has many small, thin flows that are characterized by being vesicular and amygdaloidal. The upper flow unit (UFU) conformably overlies the MFU and is believed to be composed of one or two massive flows, this flow unit outcrops along the Bay of Fundy shores (Webster et al., 2006).

The Annapolis Valley is underlain by Triassic sedimentary rocks of the Blomidon and Wolfville Formations. It is flanked to the north by the Jurassic NMB and to the south by the Meguma terrane and South Mountain Batholith (Keppie, 2000). The relative contrast in strength of the basalt units, and to a larger extent the Triassic sediments and igneous rocks are clearly expressed in the area's topography

Surficial geology of the area (Fig. 2.1) is characterized by modern fluvial and organic deposits, as well as glaciofluvial deposits and till. Glaciofluvial deposits in the project area consist of subaerial proglacial fan sediments and ice contact sediments made of sand, gravel and boulders. Ice contact sediments form the eskers, kames and morainic accumulations in the region (Bolduc et al., 2006). Till in the area is characterized by the muddy Lawrencetown Till (Stea et al., 1998). This till is a result of the Wisconsinan Laurentide ice sheet and repeated glaciation events until ca. 12 ka (Stea and Mott, 1998).

The till deposited consists of 20-30% gravel, 30-40% sand and 30-50% silt and clay which gives the material low permeability (Lewis et al., 1998).

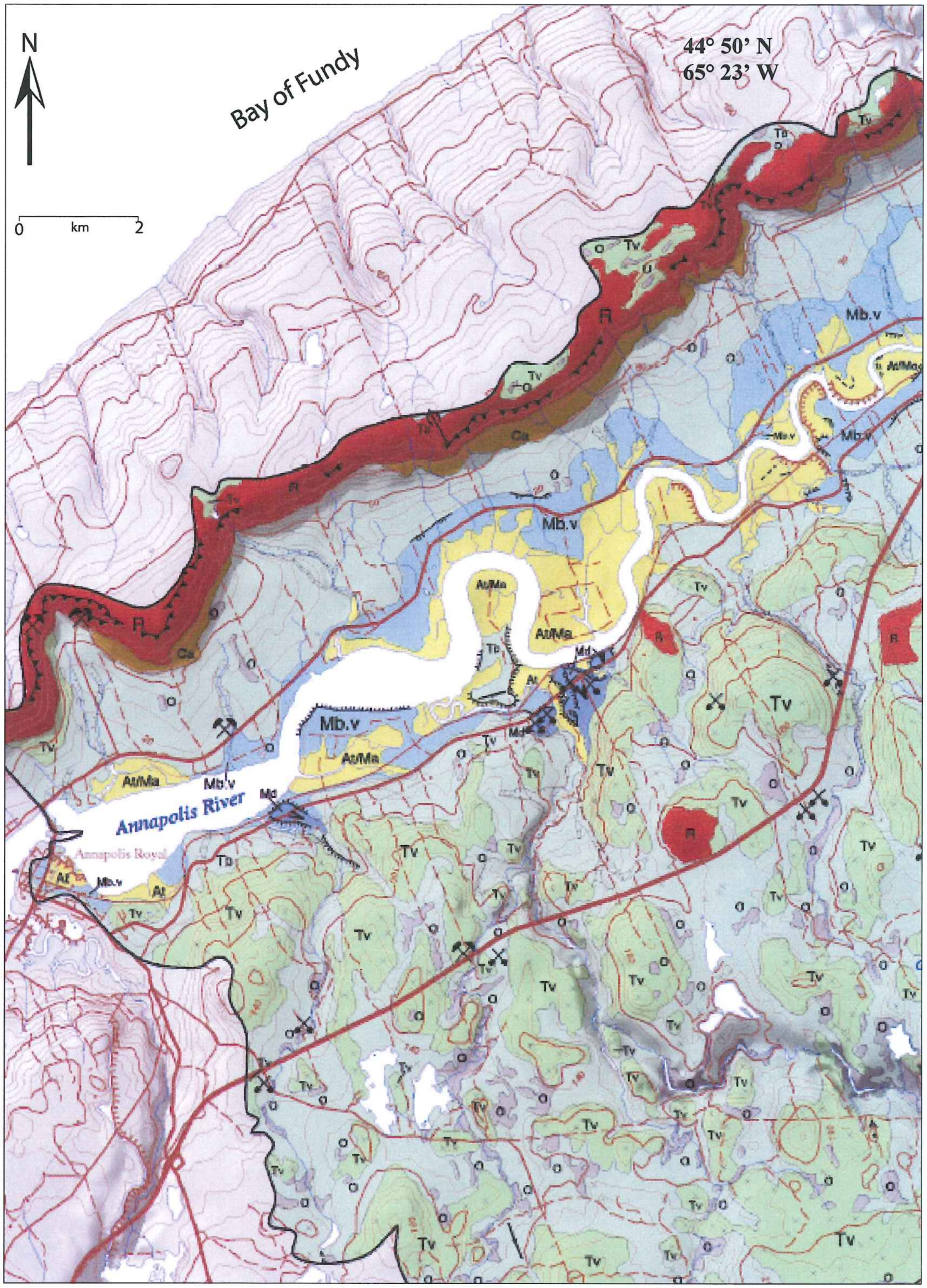



**Figure 2.1 – Project Area Surficial Geology** (After Bolduc et al., 2006) Surficial geology map of the study area (*see Appendix A – Annapolis Surficial Geology Map - Legend*). Note there are no eskers mapped and very few drumlins.

### 2.1.3 Project Area Suitability

The project area has been chosen because of the availability of LiDAR imagery, its general lack of anthropogenic influence, and that the region's recent glacial history has been studied at a higher level than most locations in Nova Scotia. The area was extensively mapped and studied (Stea et al., 1998 and Bolduc et al., 2006) using 1:26,000 aerial photos, satellite data and field observations. Because the area was recently mapped it allows a good comparison between identified surficial landforms and newly identified landforms found on LiDAR imagery. Many well preserved and documented glacial landforms exist in the area including kame and esker deposits that are readily visible on aerial photos and LiDAR imagery. The area has little fluvial and marine influence, and has a normal geothermal gradient yet covers diversified terrain including the Bay of Fundy coast, North Mountain and Annapolis Valley lowlands.

## 2.2 Deglacial Concepts

### 2.2.1 Deglacial Ice Dynamics

During deglaciation, ice flow continues to be controlled by the surface gradient of the ice mass. Deglaciation of an ice sheet, ice cap, or valley type glacier can occur by simple thinning and stagnation or by systematic retreat of the ice margin. The style of deglaciation in a region is controlled by a number of variables, including the rate of temperature and precipitation change in the ablation and accumulation zones, as well as local factors, most importantly topography but also including aspect, geothermal flux, basal shear strength and basal hydrology. Deglaciation is also effected by the presence of lakes and oceans at the glacier margin (Bennett and Glasser, 2004).

There are two general models that describe ice dynamics during deglaciation. The first model is down-wasting by areal stagnation where the equilibrium line rises in elevation quickly, due to climate change, leading to lower accumulation rates and higher ablation rates. Once this process begins the glacier can decay rather rapidly with little or no forward flow (Bennett and Glasser, 2004). The second scenario is described by active deglaciation caused by ice-marginal retreat. In this case the glacier continues to flow forward while it decays through contraction and retreat of its margins, which can be accelerated by calving in glaciomarine environments. This process can occur at variable rates depending on seasonal accumulation and ablation (Bennett and Glasser, 2004).

As it is unlikely that an entire glacier will be deprived of any accumulation while it is decaying, many geologists believe that areal stagnation of a glacier is only of regional or local importance (Bennett and Glasser, 2004). In the broad case of deglaciation, ablation is always maximum at the ice margins and minimum at the ice divide, where ice flow velocity is zero. This difference maintains a gradient on the glacier surface which leads to basal shear stress and a forward flow away from the ice divide. Since the areal stagnation model is believed to be true only on a local or regional scale, where very low angle ice sheets or glaciers exist, the entire ice complex may have seasonal readvances, stagnant periods, surges and maybe prolonged periods of readvances. Although the two deglaciation models are basic in their approach, actual deglaciation is rarely uniform as suggested either model (Bennett and Glasser, 2004).

### 2.2.2 The Morphosequence Concept

The morphosequence concept was first introduced by R.H. Jahns (1941) as a way to classify glacial landforms. The concept describes 'landforms composed of meltwater deposits, from more collapsed forms due to melting of ice blocks at the head or upstream parts of outwash, to progressively less collapsed forms downstream' (Koteff and Pessl, 1981). In the case of morphosequences, the term 'sequence', has no relation to time other then its relation to other sequences. A sequence is described by Koteff and Pessl (1981) as 'a body of stratified drift laid down, layer upon layer, by melt water at and beyond the margin of a glacier, while deposition was controlled by a specific base level'.

The original morphosequences proposed by Jahns covered only fluvial sediments but have since been expanded to include lacustrine and marine deposits. There are currently eight morphosequences (Koteff, 1974) that are differentiated by their depositional environment; fluvial, lacustrine and marine. These morphosequences are further divided to describe them as in contact with a stagnant ice margin or whether they were related to an end moraine (Fig. 2.2) (Koteff and Pessl, 1981).

Textural distribution, base-level control and profiles of the deposits are distinguishing physical characteristics of the sequences. Like any water-laid deposit, the texture (grain size) is coarser near the source of outwash and becomes progressively fine grained downstream as flow velocity drops, allowing suspended sediment to be deposited. Depending on the size and length of a deposit the textural boundaries may be difficult to observe. Many deposits can have gravel found associated with fine sand and vice versa. In the general case, textural gradation downstream from the source area is generally persistent over most sequences (Koteff and Pessl, 1981).

The presence of base level control is very important in distinguishing one morphosequence from another. Base level controls can be in the form of spillways that are underlain by bedrock or till, previously deposited sands and gravels, glacial lakes, oceans and stagnant ice masses (Koteff and Pessl, 1981). It is sometimes difficult to determine base level control because of erosion and sea level change but underlying bedrock is often the most durable and time resistant (Koteff and Pessl, 1981).

Another tool that can aid in distinguishing one morphosequence from another is topographic profile. When drawn in a downstream direction the profiles allow relative ages between sequences to be determined, especially when there is textural data available to distinguish proximity to outwash sources (Koteff and Pessl, 1981). Morphosequences can be used to determine whether deposition was initiated at a stagnant or live ice margin. The most obvious sequences that are associated with stagnant margin retreat are the heads of outwash of fluvial or lacustrine ice-contact, melt water deposits. The only outwash plains that have been attributed to live ice are those that are associated with end moraines (Koteff and Pessl, 1981). Some morphosequences can be used to determine the width of stagnant zones. The length of eskers and ice-channel fillings can be used to determine areas where ice was decaying and depositing these features. Live ice is typically associated with end moraines because the ice movement is needed to construct the moraines by pushing material forward.

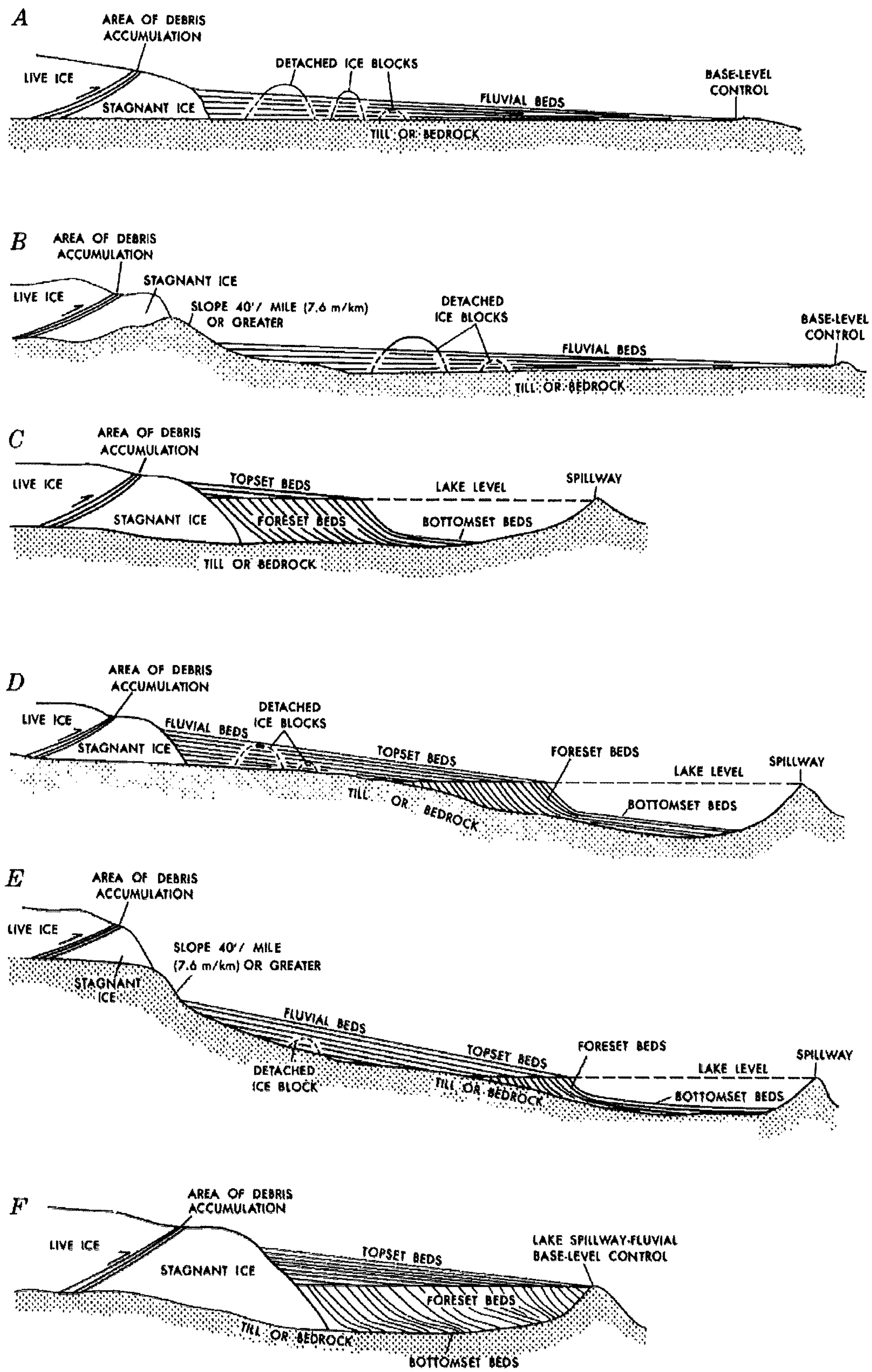



**Figure 2.2 Diagramatic profiles of morphosequences** (after Koteff, 1974). Detached ice blocks and stagnant ice masses are sites of future collapsed ice-contact slopes. A) fluvial non-ice contact sequence, B) fluvial non-ice contact sequence, C) lacustrine ice-contact sequence, D) fluvial-lacustrine ice-contact sequence, E) fluvial-lacustrine non-ice-contact sequence , F) lacustrine-fluvial ice-contact sequence.

## 2.3 Ice Dynamics – Current Conceptual Model

There have been many studies completed each contributing to the currently accepted conceptual model of deglaciation for the Annapolis Valley and North Mountain. The most recent publication has been by Shaw et al. (2006), others include the Annapolis Valley Surficial Geology Map (Bolduc et al., 2006), Stea et al. (1998) and Stea and Mott (1998).

Glacial maximum occurred during the late Wisconsinan when glaciers extended outwards to the shelf edges of Atlantic Canada. It is believed that deglaciation began 18 ka with calving occurring in the Gulf of Maine and off the south coast of Nova Scotia. The cause of the increasing rate of deglaciation can be attributed to rising sea levels, which are also a direct result of melting glacial ice, which spurred calving at marine margins. This increased calving led to faster flowing ice and increased basal melting leading to more flow towards calving bays. Once the glaciers had retreated to land they were subject to warming climates and continued melting. Scotian Phase glaciation occurred 18 to 15 ka with an ice divide (Scotian Ice Divide) centered over the longitudinal axis of Nova Scotia. Ice flows from the Scotian Ice Divide are marked by striae trending northwestward toward the North Mountain cuesta and southeastward toward the Atlantic Ocean (Stea et al., 1998). By 13 ka the glacial margin had retreated to the present day coastline marking Chignecto Phase (13 – 12.5 ka) (Fig. 2.3) glaciation. Small, separate ice-caps were created from the melting of the Scotian Ice Divide during this phase (Stea et al., 1998) and flow may have become blocked by the North Mountain cuesta. Significant climate warming after 12.5 ka allowed the Chignecto Phase glaciers to retreat to small terrestrial ice centers (Stea et al., 1998). During the Collins Pond Phase

(11 ka) some small centers of glaciation were reactivated by climatic deterioration but with renewed climatic warming ice cover in the area, and surrounding regions, was gone by 10 ka (Stea et al., 1998) (Fig. 2.3).

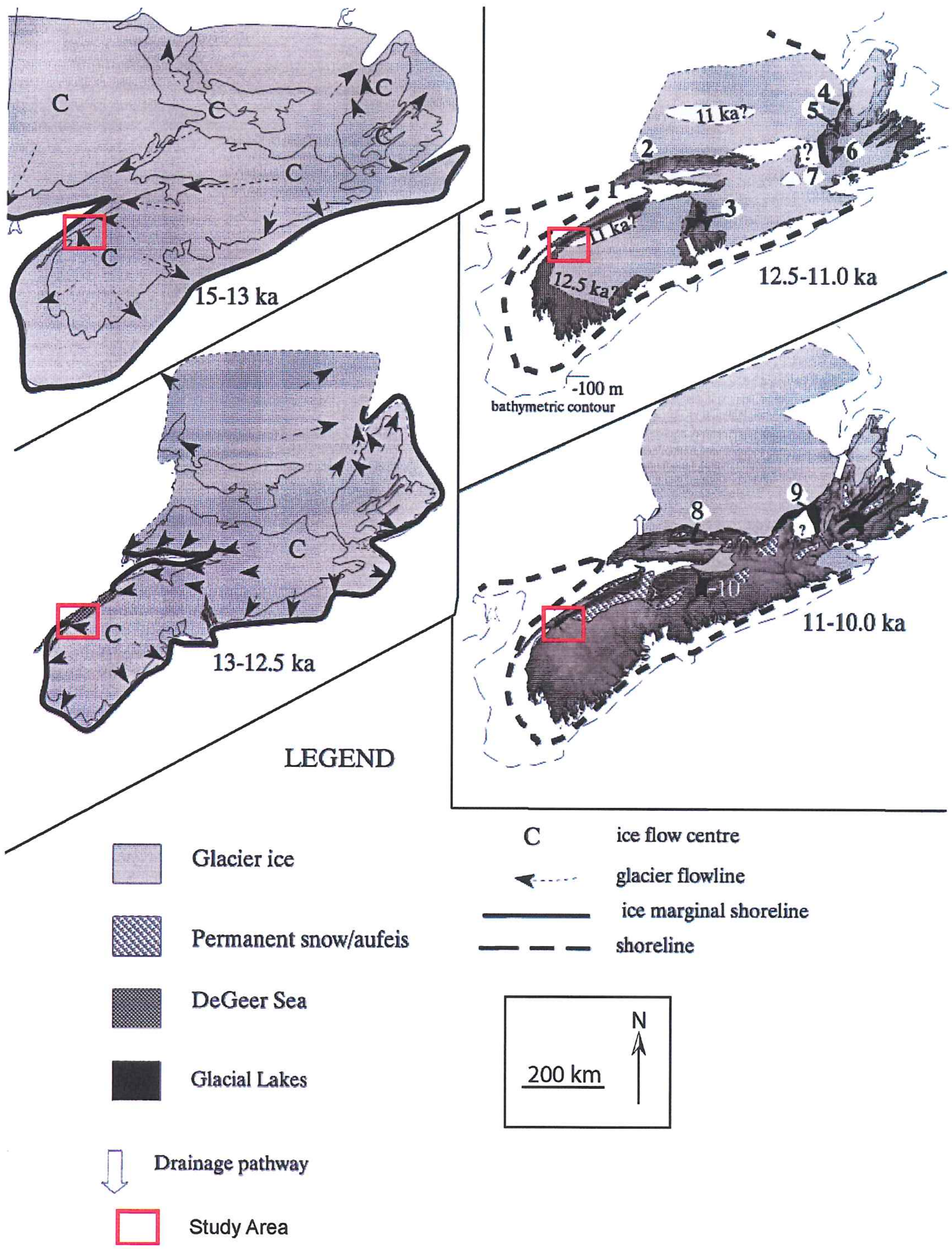



**Figure 2.3 Nova Scotia Deglaciation (15 – 10 ka)** (after Stea and Mott, 1998). Conceptual model of deglaciation for Nova Scotia showing the LiDAR study area and progressive deglaciation from 15 to 10 ka.

# CHAPTER 3 METHODOLOGY

## 3.1 LiDAR Technology

### 3.1.1 Principals and Concepts

Light detection and ranging (LiDAR) technology used in this project consists of three main components; a high-precision global positioning system (GPS), an inertial measurement unit (IMU) and a laser ranging system (Webster et al., 2006). All components are mounted on a survey aircraft (Fig. 3.0) with the exception of independent GPS base stations, one used as a control for the GPS on the aircraft and the other used for independent validation. The data from the GPS is used as a control in post-processing to align data to decimeter level precision. LiDAR systems are valuable for ranging applications because of their relatively small size and ability to release high energy pulses in very short intervals (Wehr and Lohr, 1999).

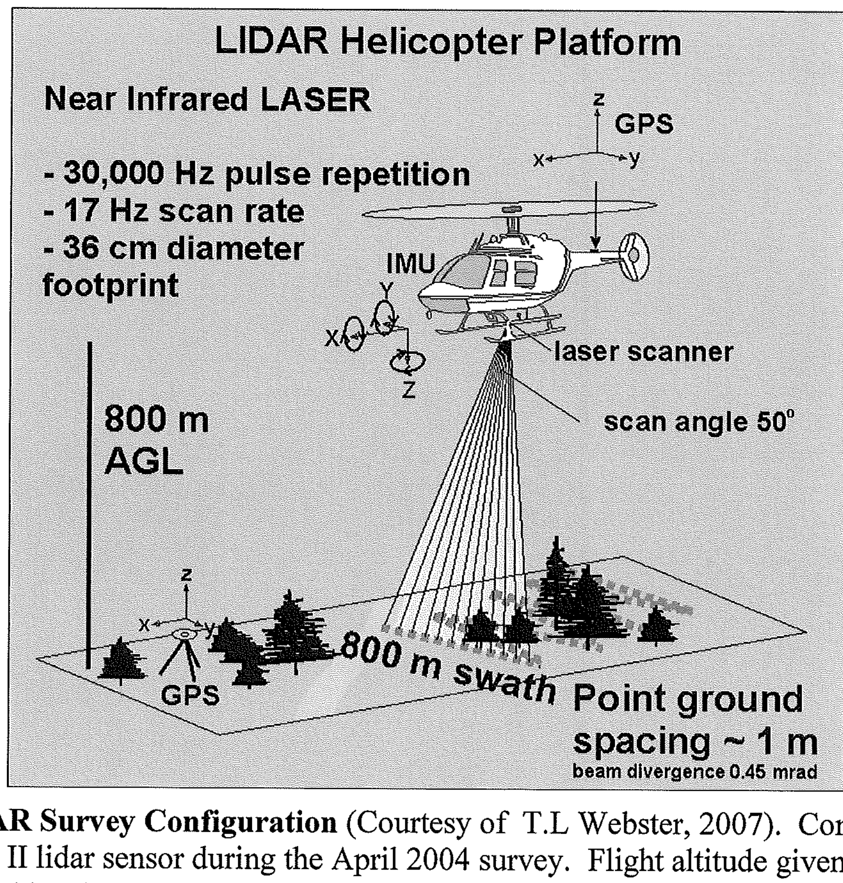



**Figure 3.0 LiDAR Survey Configuration** (Courtesy of T.L Webster, 2007). Configuration of the Mark II lidar sensor during the April 2004 survey. Flight altitude given in meters above ground level (AGL)

The laser ranging system determines the distance to ground targets by measuring the return travel time of a short-duration laser pulse. The laser system is set up so the transmitting and receiving apertures have the same optical path which enables ground points illuminated by the laser to always be within field of view of the optical receiver (Wehr and Lohr, 1999) giving continuous data coverage. The GPS, along with the inertial measurement unit is used to measure and record the aircraft's position (x, y, z) while the scan angle and range allows the laser returns to be positioned in three-dimensional space (Brennan and Webster, 2006). The receivers can then determine the actual distance to the ground for each point by combining information provided by the IMU, on-board GPS, and laser system. The amount of data points collected depends on the setup of the LiDAR system, including frequency and ground spacing.

The reflected pulse is capable of measuring multiple near ground hits if the on-ground laser diameter covers more then one target, where each target is vertically distinct, for example, a tree and the nearby forest floor, or a building edge and adjacent pavement (Haugerud et al., 2003). Most sensors, including the Mark II used in this survey, are capable of recording the first and last pulse, but these are not necessarily non-ground and ground points. The LiDAR vendor usually classifies the data into ground and non-ground targets. Because this project is concerned with mapping surficial landforms, ground hits are more important for the survey as they provide accurate points for a detailed 'bald Earth' digital elevation model.

The LiDAR survey and data collection for the study area was completed in 2004 by Terra Remote Sensing Inc. of Sidney, British Columbia under contract to the Applied Geomatics Research Group of the Nova Scotia Community College. The survey flights were conducted between April 20$^{th}$ and April 25$^{th}$ while deciduous trees were leafless, allowing the highest possible return of ground targets (Brennan and Webster, 2006). A Mark II LiDAR sensor was mounted on the survey aircraft and flown at an altitude of 800 m above ground level (AGL) with a mirror scan rate of 17 Hz, a laser wavelength of 1064 nm, and a pulse rate of 30 kHz. At this configuration the ground footprint diameter of the laser was 0.36 m. The sensor recorded both the first and last returns during the mission (Brennan and Webster, 2006).

Terra Remote Sensing Inc. delivered the LiDAR data to the Applied Geomatics Research Group (AGRG) at the Centre of Geographic Sciences (COGS) in Middleton, Nova Scotia as both ground and non-ground ASCII files that were divided into 4 km x 4 km tile sets which covered the entire survey area (Fig. 2.0). Each data point consisted of the following attributes: easting, northing, ellipsoidal height, orthometric height [Canadian Geodetic Vertical Datum 1928 (CGVD28)], GPS time, echo code, flight line number and LiDAR intensity (Brennan and Webster, 2006). The LiDAR ground points were then used to construct the 2 m resolution 'bald-earth' digital elevation model that was analyzed for use in this project.

### 3.1.2 LiDAR Validation

Although LiDAR systems are becoming highly advanced and accurate there are still errors that can occur which can affect the quality of the data. These errors can be due to mission planning variables, data classification and calibration. Inability to independently validate the data may lead to unreliable results (Webster, 2005). LiDAR data's precision comes from its ability to attain horizontal and vertical accuracy to within

±30cm depending on flight altitude and ground conditions during the survey (Brennan and Webster, 2006). To ensure an accurate survey it is necessary to understand the intended target prior to data acquisition. For example, in the case of this project where it was required to produce a 'bald Earth' DEM, it was advantageous that the survey was flown during the spring while leaf cover was minimal and shrub growth was limited. This ensures a maximum return of ground points which leads to a detailed representation of the actual ground surface. To further maximize ground point accuracy and return, it is better to have a moderate (.3-.5m) beam footprint so that in the case of forested areas some of the laser energy reaches the actual ground surface through the canopy (Webster, 2005).

Due to this and other projects' need for highly precise measurements of surficial landforms it was necessary to ensure the LiDAR data was accurate to within 15 cm of measured GPS heights with 95% of the data to be within 30 cm (Webster, 2005). A real-time kinetic GPS survey was completed in October 2004 utilizing a Leica GPS System 500 by AGRG staff. This system consisted of two base stations and one rover. GPS data within the LiDAR survey area was collected with a height precision better than 3 cm. The GPS heights were then compared to the LiDAR point heights using a technique that compares LiDAR points to a search radius around the given GPS points (Brennan and Webster, 2006). The LiDAR data for our study area was validated using this method which is described in greater detail in Webster and Dias (2006).

### 3.2 GIS Technology

LiDAR data for the project area were imported into ArcGIS, a geographic information system (GIS) software program developed by Environmental Systems

Research Institute, Inc. (ESRI). The program allows manipulation and visualization of spatial data that aids in interpreting vast quantities of geographic data. For the purpose of this study, ArcGIS allowed the LiDAR data to be easily viewed and interpreted using various functions of the program.

ArcGIS allows the user to specify a vertical exaggeration of elevation values. This is useful because glacial landforms in the area have typically less than 10 m relief and are difficult to distinguish without some vertical exaggeration. The hillshade feature of the program is particularly useful when dealing with very small scale linear features such as glacial drumlinoids or fluted terrain. The function creates a hypothetical light source of the user's choice, with an angular sun direction between 0° and 360°, and an elevation angle of between 0°-90° on the DEM (ESRI, 2005). The program then graphically interprets where topography will be illuminated or shaded. The resulting visual contrast between sun and shade allows enhanced visualization and interpretation of the data.

The ability of the program to provide highly detailed topographic profiles of surficial landforms aids in determining the type of landform and can provide information about ice flow direction during deposition or formation. Profiles are used in this study to gain an understanding of the esker system north of Annapolis Royal and to determine ice flow direction from drumlins. ArcGIS can also compute detailed volume calculations of surficial deposits which aids in understanding the complete story of deglaciation. This tool is also commercially viable for use in the aggregate industry where sand and gravel from glacial deposits are highly sought after and volume calculations aid in targeting further resource exploration.

Another simple, yet powerful tool of ArcGIS is its ability to overlay digitally published surficial geology maps on top of the LiDAR generated DEM. This allows comparison between previously mapped landforms and new landforms identified on the LiDAR data.

### 3.3 Mapping Methods

Much like previous mapping techniques utilizing air photos and satellite imagery, shaded relief DEM's were compared with the current Annapolis Valley Surficial Geology Map at 1:100,000 scale (Bolduc et al., 2006). Features on this map were compared to visible features on the DEM to provide a visual reference to use when looking for previously unidentified landforms. The main landforms related to glaciation that are present in the study area include drumlinoids, eskers, crag and tails, drumlins and wave-cut terraces. Drumlinoids and streamlined landforms range in length from less than 10 meters to nearly 1 kilometer, their relief is significantly less than eskers (1-5 m) and they require higher resolution imagery to be identified. There is some debate regarding the origin of these landforms. Some researchers believe they are caused by large volumes of flooding meltwater at the base of ice, while others believe the landforms are caused by the direct effect of the ice movement and pressure, with little influence from meltwater (Liverman et al., 2006). Eskers are defined as sinuous ridges of massive and stratified sand and gravel that are generally discontinuous. They are formed from subglacial and englacial meltwater release during glacial retreat (Gosse et al., 1999). Eskers are relatively easy to identify using remote sensing because they have relatively high relief (10 m) and are somewhat linear features. They are key to understanding deglaciation because they commonly form at decaying glacial margins. Drumlins are spoon-shaped hills that are believed to be developed by overlying glacial pressure that molds and reshapes till. These landforms can range in length from 400 – 2000 meters and range in height from 5 to 50 meters. Drumlins provide good ice flow direction indicators with ice flowing towards the steep (stoss) side of the landform (Fig. 4.10) (Chernicoff & Whitney, 2002). Crag and tail landforms are formed when a glacier or ice-sheet moves over resistant rock outcroppings, which protects sediments behind it from erosion, and forms streamlined landforms in the direction of ice flow. Although not confirmed by field mapping, landforms resembling crag and tail features have been identified on the DEM (R.R Stea, personal communication, 2007). Wave-cut terraces are caused by erosion of material along marine coast lines by wave and tidal action. These terraces are found above sea level when relative sea level falls leaving the terrace stranded. They are easily recognizable due to their proximity to large bodies of water and linear shape. When identified they are the most important marine limit indicators. Wave cut terraces in the project area are readily identified and allow an accurate measure of elevation and marine limit.

# CHAPTER 4 RESULTS

## 4.1 Surficial Landforms

The application of LiDAR to assist in visualizing the project area has led to the discovery of many surficial and glacial landforms that had not been identified in previous mapping campaigns by Bolduc et al. (2006) (Fig. 2.1) and Stea and Mott (1998). Newly identified landforms (Fig. 4.0) range from meso-scale glacial drumlinoids to eskers, which run for nearly 1 km and have vertical relief of >10 meters. A large esker system, along with two large, north-northwest trending drumlins (Fig. 4.1) were identified south of Annapolis Royal. This system, although very close to major highways, was not identified with previous mapping techniques, although it appears the northernmost drumlin is currently being mined for aggregate or fill. Numerous other eskers were identified throughout the project area, especially in the Annapolis Valley area south of the Annapolis River.

Application of 'hillshade' digital elevation models has allowed identification of glacial drumlinoids (Fig. 4.2) over the entire project area in the Annapolis Valley and in areas of the North Mountain. These landforms were not previously recorded. Orientations of the drumlinoids were measured at multiple locations and plotted as rose diagrams on a digital elevation model of the project area (Fig. 5.0). There is certainty that these are not artifacts of processing because they are only clearly visible when illuminated from azimuths and sun angles near 225°/045°. The survey flight was also flown in a northeast/southwest pattern and on average the landforms have a trend of 310-325°.

Previously identified wave-cut terraces along the southern shores of the Bay of Fundy are visible on the DEM. The LiDAR DEM has revealed that these wave cut terraces truncate an esker system (Fig. 4.3) on North Mountain, north of Annapolis Royal at an average of 37 m above sea level (Fig. 4.5, 4.6). The North Mountain esker system also has landforms that are not visible on other eskers in the study area. There are fan like features (Fig. 4.4) that are visible on the flanks of the various eskers in the system which appear to have significance in regards to deglacial ice dynamics and morphosequences.

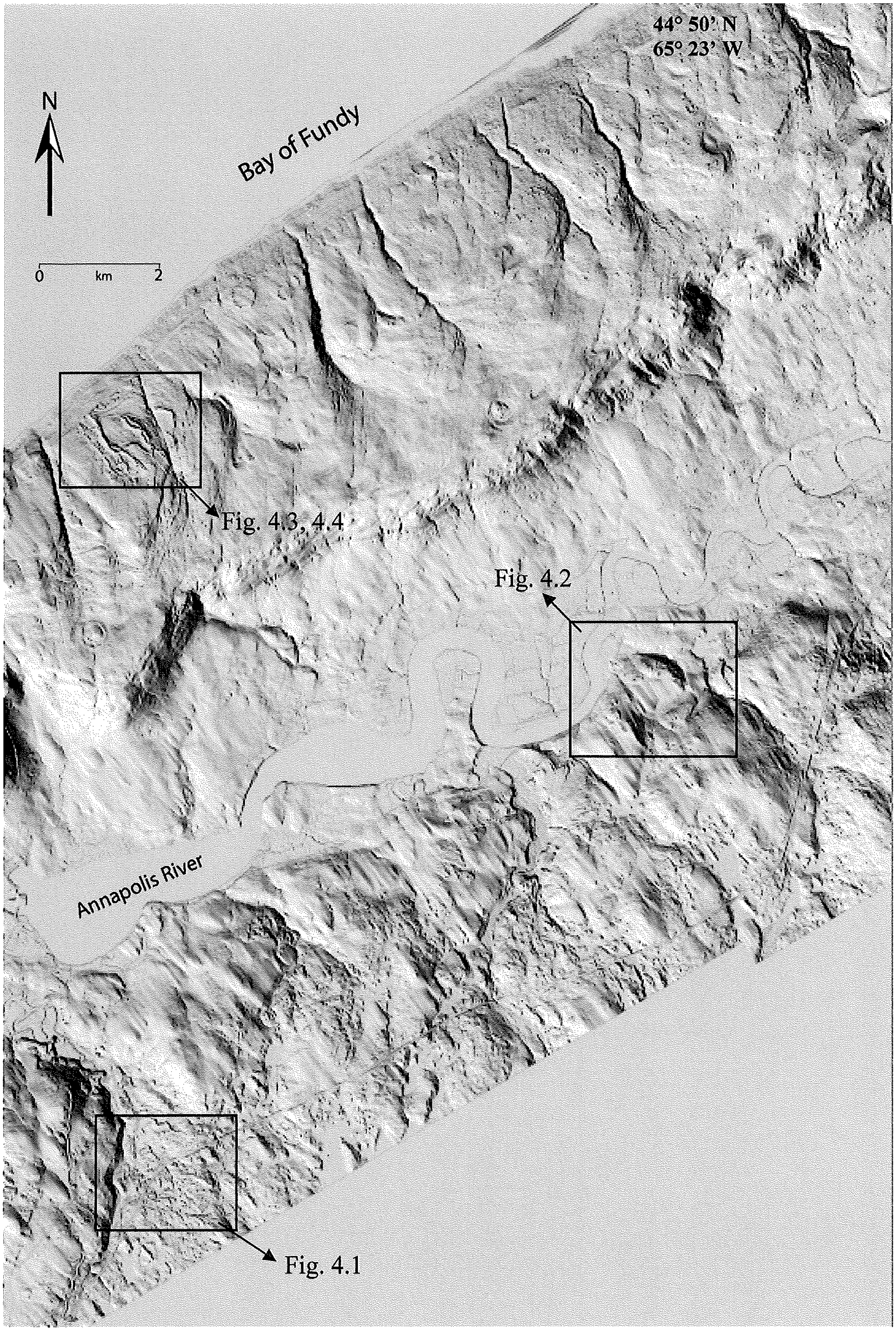



**Figure 4.0 – Location of newly identified features.** This image shows general areas where new landforms have been identified. Each box corresponds to the following figures which show in detail the newly identified landforms.

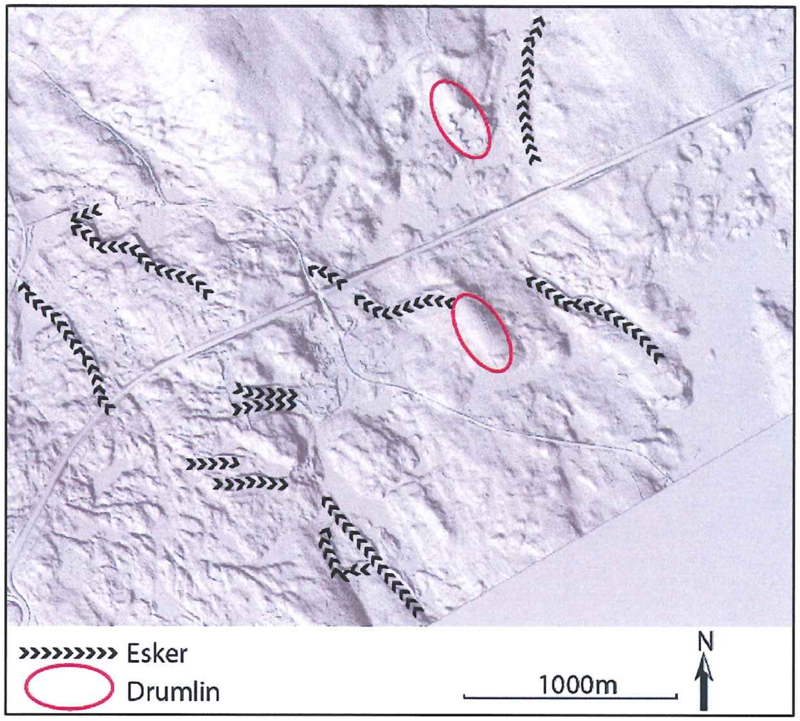



**Figure 4.1 – Newly identified Esker System.** This esker system and corresponding drumlins were not identified during previous mapping campaigns. The eskers average 600m in length and the drumlins are nearly 500m long. These landforms are both significant in determining deglacial history. **Image shaded from 225°, light source azimuth 45°, vertical exaggeration 5x.*

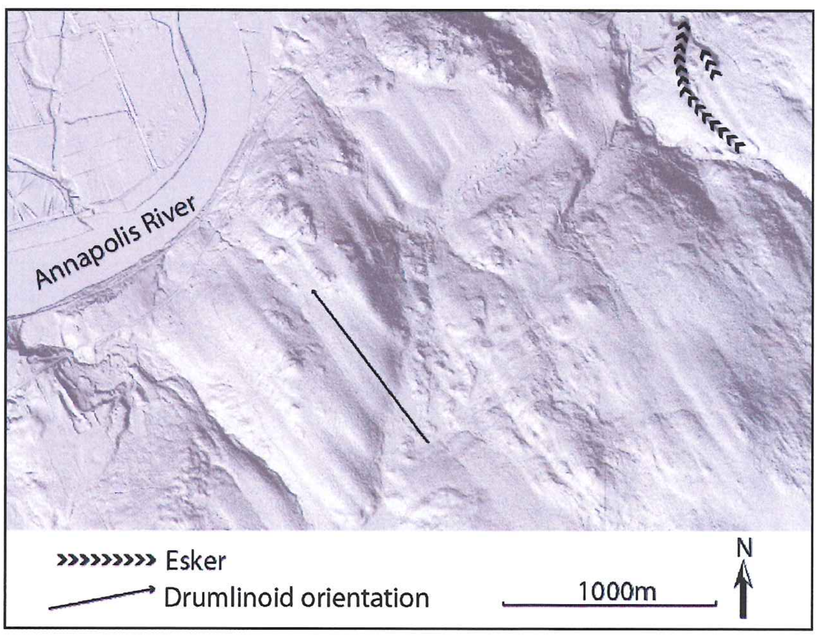



**Figure 4.2 - Drumlinoids.** Drumlinoids are clearly visible in the image trending to the north-northwest (310°-325°). These landforms are visible over large areas of the Annapolis Valley and portions of North Mountain, and are only visible at this scale with LiDAR imagery. **Image shaded from 225°, light source azimuth 45°, vertical exaggeration 5x.*

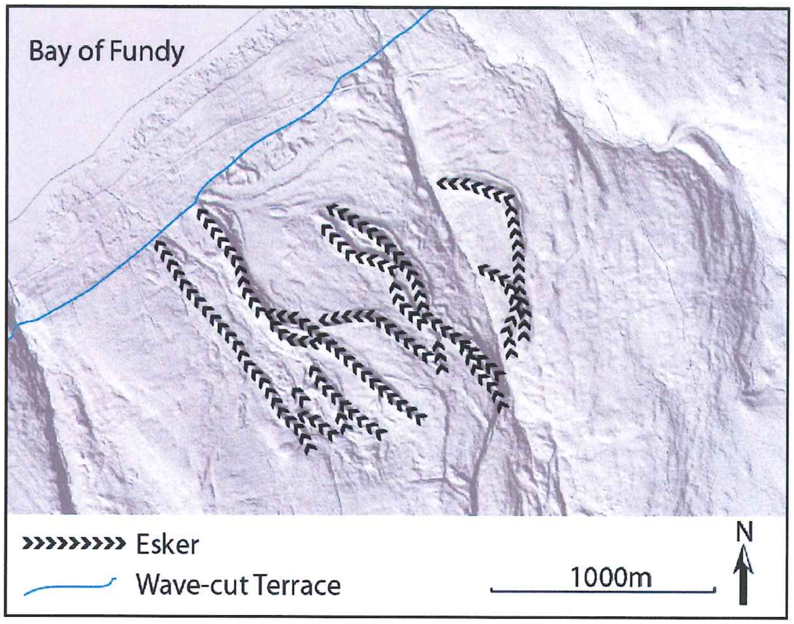



**Figure 4.3 - North Mountain Esker System, Wave-cut Terrace.** This image shows an esker system on North Mountain that has been truncated by post-glacial sea level rise. The relative chronology is important in better understanding the deglacial history. **Image shaded from 225°, light source azimuth 45°, vertical exaggeration 5x.*

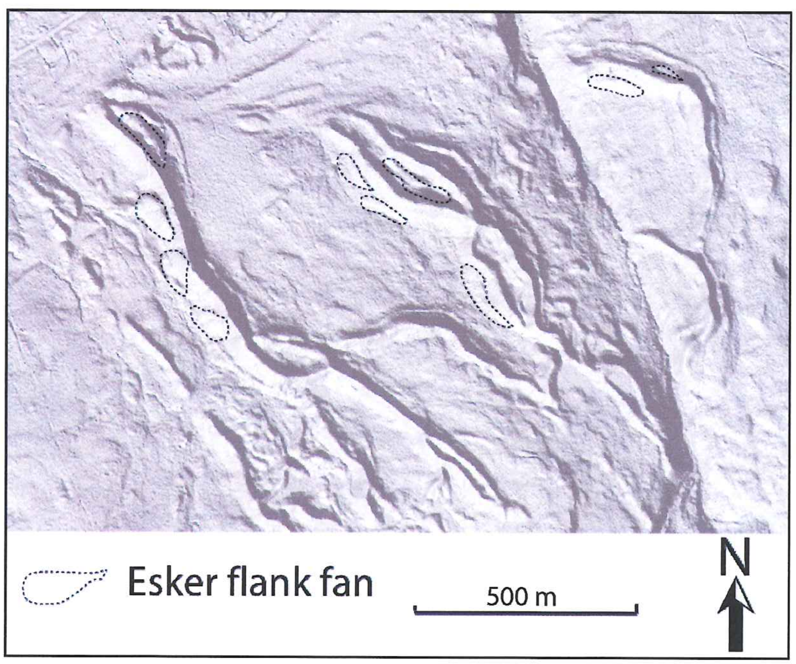



**Figure 4.4 - Esker Flank Fans.** The highlighted esker flank fans have not been documented to date in Nova Scotia. These fans may be significant in determining glacial retreat timelines for the local area. **Image shaded from 225°, light source azimuth 45°, vertical exaggeration 5x.*

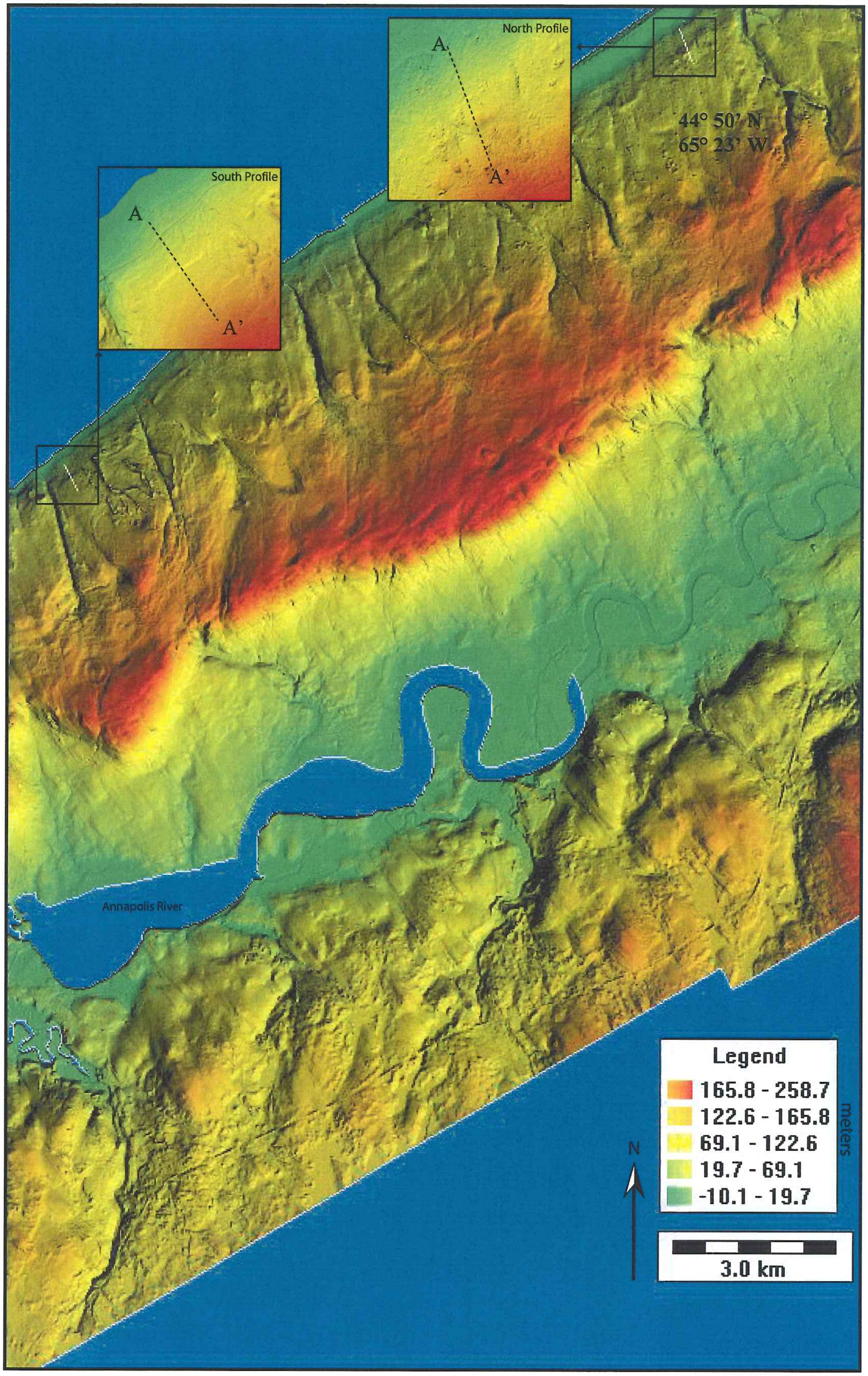



**Figure 4.5 – Wave Cut Terrace Profile Location.** Locations of profiles across the wave cut terrace at the southern and northern extents of the study area. **Image shaded from 145°, light source azimuth 40°, vertical exaggeration 5x.*


**Figure 4.6 – Wave Cut Terrace Profiles.** These profiles are perpendicular to the wave cut terrace at the south and north ends of the study area. There is little change in elevation over the study area.

Within the project area there are 38 previously undocumented surficial and glacial landforms, with the majority being isolated eskers, and the widespread glacial drumlinoids found in the Annapolis Valley. Table 4.0 summarizes the number of new landforms identified as compared with landforms identified on the Annapolis Valley Surficial Geology Map (Bolduc et al., 2006).

**Table 4.0 Identified Landforms**

**these features were not included in the mapping campaign*

| Landform | Number Identified on 2006 GSC Map | Number Identified on LiDAR Imagery |
|---|---|---|
| **Eskers (fragments)** | 2 | 23 |
| **Esker Flank Fans** | not mapped* | 10 |
| **Moraines** | 0 | 0 |
| **Drumlins** | 1 | 3 |
| **Drumlinoids** | 0 | Cover nearly all of Annapolis Valley in area |
| **Wave-cut Terraces** | not mapped* | 5 |

## 4.2 Spatial Relationships

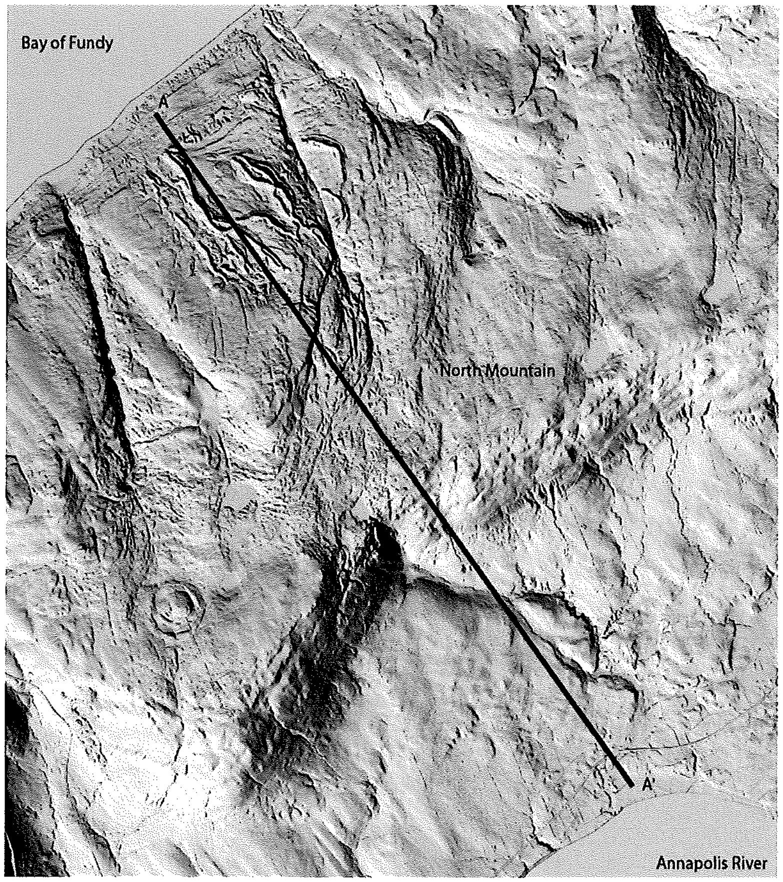
The spatial relationships of the newly identified surficial landforms and some distinct known landforms were examined using ArcGIS, Global Mapper and RiverTools software to provide a clearer view of topographic control on the individual deposits. Table 4.1 summarizes the spatial relationships of two esker systems in the project area; one on North Mountain, the other in the Annapolis Valley. Although there are numerous other eskers in the project area, these two sites have been chosen for measurement because of the high concentration of eskers in each particular area.

| Landform | Location | Max Elev. (m) | Min Elev. (m) | Difference (m) | Length (m) | Slope* |
|---|---|---|---|---|---|---|
| Esker | North Mountain | 131 | 40.6 | 90.4 | 1173.8 | 0.077015 |
| Esker | North Mountain | 132.9 | 117.4 | 15.5 | 230.8 | 0.067158 |
| Esker | North Mountain | 131.3 | 110.1 | 21.2 | 388.7 | 0.054541 |
| Esker | North Mountain | 147.6 | 40.2 | 107.4 | 1523.2 | 0.070509 |
| Esker | North Mountain | 142.2 | 102.7 | 39.5 | 646.6 | 0.061089 |
| Esker | North Mountain | 141.4 | 66.5 | 74.9 | 1266.6 | 0.059135 |
| Esker | North Mountain | 129.4 | 85.5 | 43.9 | 425.9 | 0.103076 |
| Esker | North Mountain | 141.8 | 112.3 | 29.5 | 679.6 | 0.043408 |
| | **Averages** | 137.2 | 84.4 | 52.7 | 791.9 | $6.69 \times 10^{-2}$ |

| andform | Location | Max Elev. (m) | Min Elev. (m) | Difference (m) | Length (m) | Slope* |
|---|---|---|---|---|---|---|
| Esker | Annapolis V. | 122.4 | 72.7 | 49.7 | 807 | 0.061586 |
| Esker | Annapolis V. | 128.4 | 123.6 | 4.8 | 282.6 | 0.016985 |
| Esker | Annapolis V. | 118.2 | 116.4 | 1.8 | 581.7 | 0.003094 |
| Esker | Annapolis V. | 119 | 116.4 | 2.6 | 678.4 | 0.003833 |
| Esker | Annapolis V. | 129.1 | 107.5 | 21.6 | 651 | 0.03318 |
| | **Averages** | 123.4 | 107.3 | 16.1 | 600.1 | $2.37 \times 10^{-2}$ |

**Table 4.1 Esker data -** **slope refers to longitudinal slope of esker*

Several topographic profiles were created using the LiDAR derived DEM's. These profiles are useful in confirming the landform classification as well as aiding in visualizing spatial control on the deposits. The first profile was created to show the varying topography of the project area in a transect running NNW-SSE across North Mountain towards Annapolis Valley (Fig. 4.7). Another profile was created running roughly perpendicular to the first that shows the relief of the North Mountain esker system in comparison with local topography (Fig. 4.8). A profile was also created on an esker flank fan located on the largest esker in the North Mountain system (Fig. 4.9). This profile enables a cross-sectional view of the fan and host esker and contrasts the difference in relief between the two. Profiles were also constructed along the longitudinal plane and cross sectional plane of a drumlin located south of Annapolis Royal (Fig. 4.10). This profile allows confirmation of the landform type and also helps aid in determining glacial flow direction during the landforms formation.



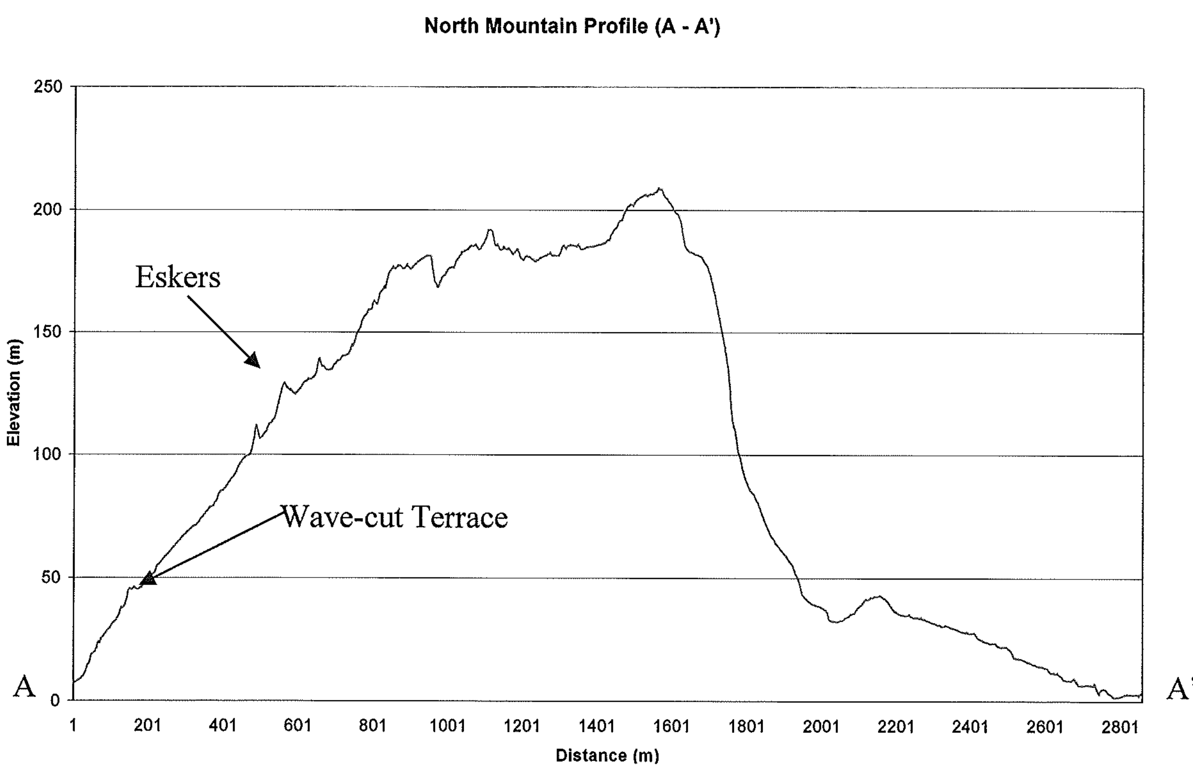
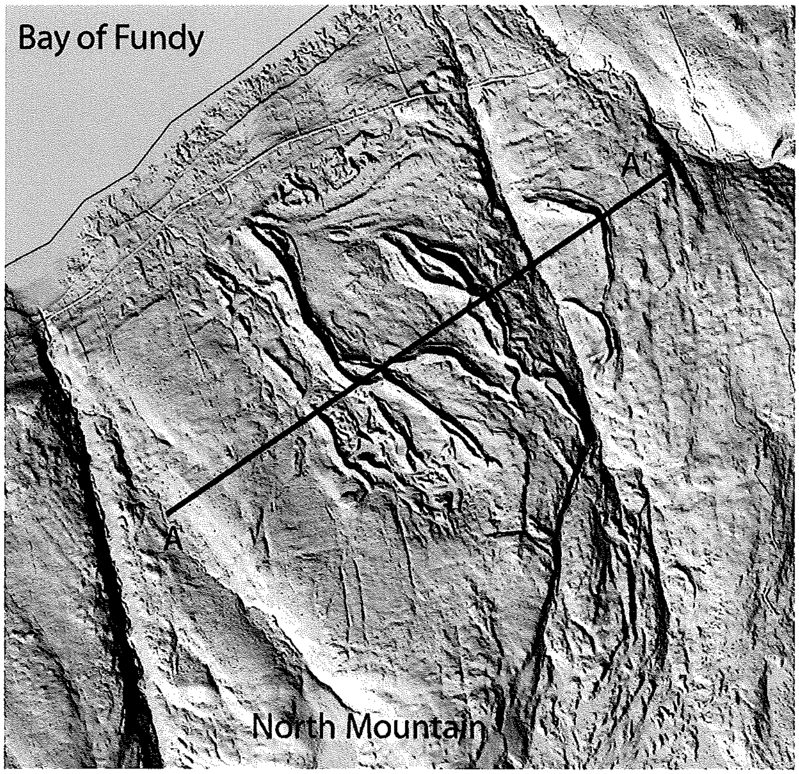




**Figure 4.7 - North Mountain Profile.** Topographic profile of North Mountain showing regional topography. Wave-cut terrace and eskers are visible on the left side of the profile.



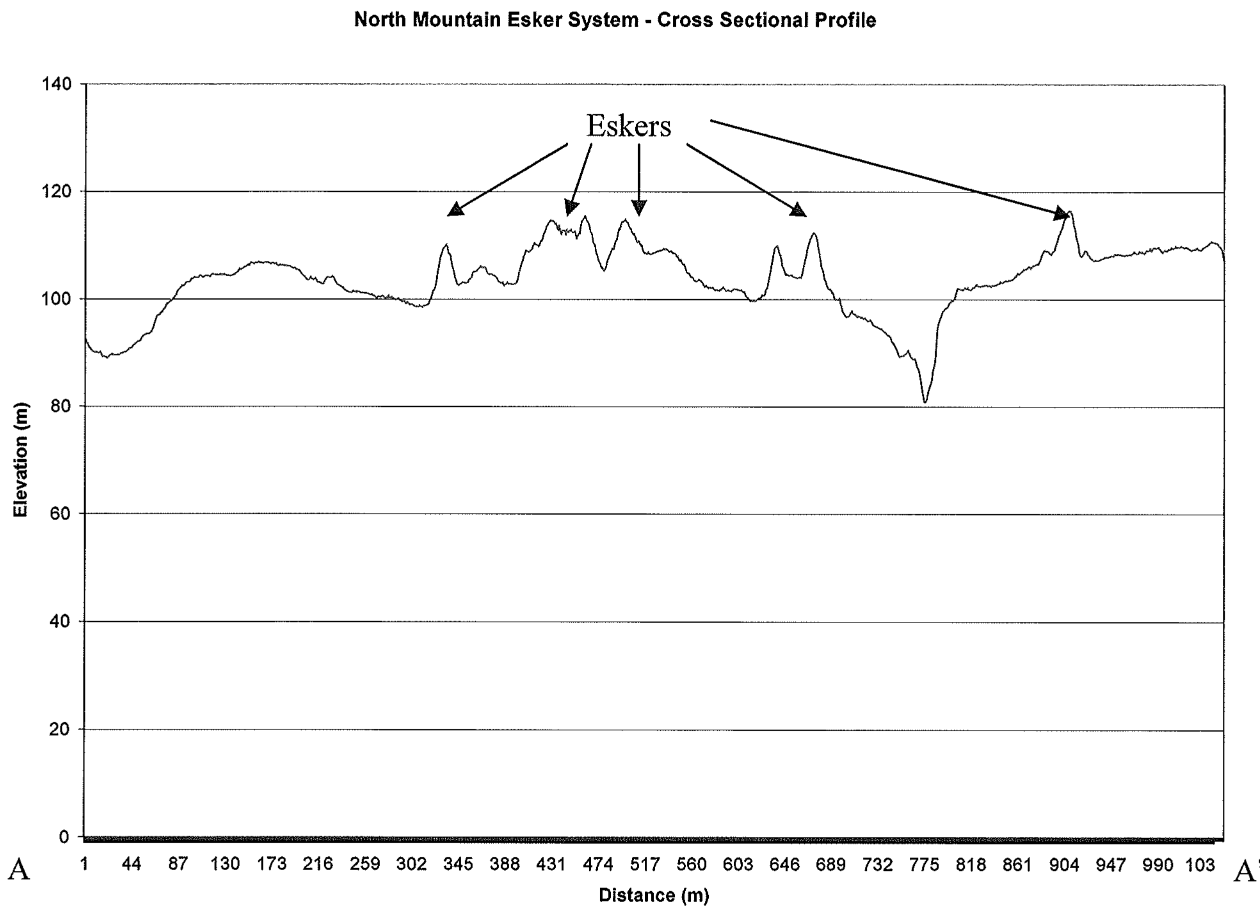




**Figure 4.8 - North Mountain Esker System.** This image shows the relief of multiple eskers as compared to regional topography on North Mountain. These profiles also aid in confirming that these features are in fact eskers and not a bedrock feature.

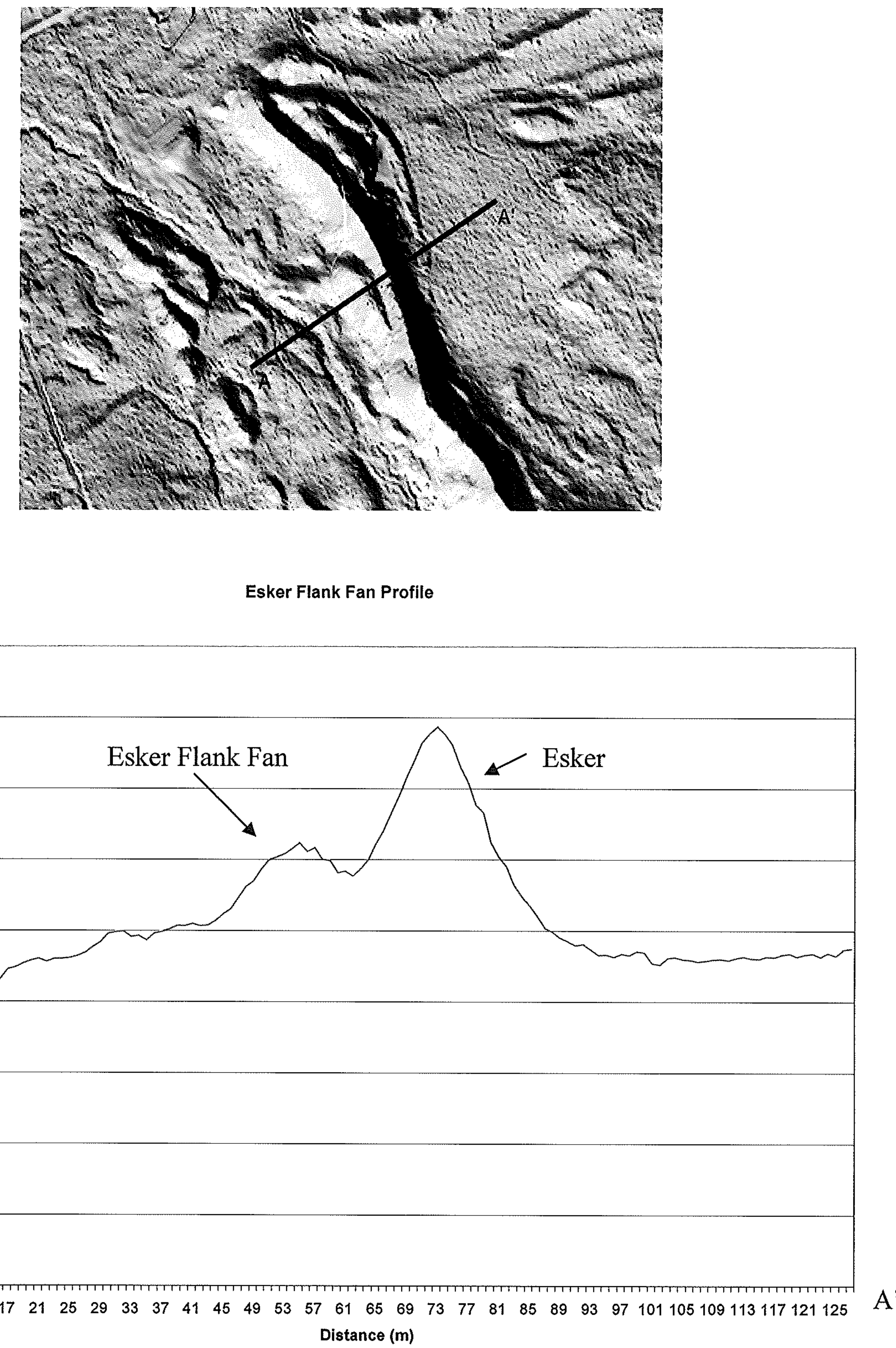



**Figure 4.9 – Esker Flank Fan Profile.** An esker flank fan is clearly visible in this profile as compared to the high relief of its host esker.

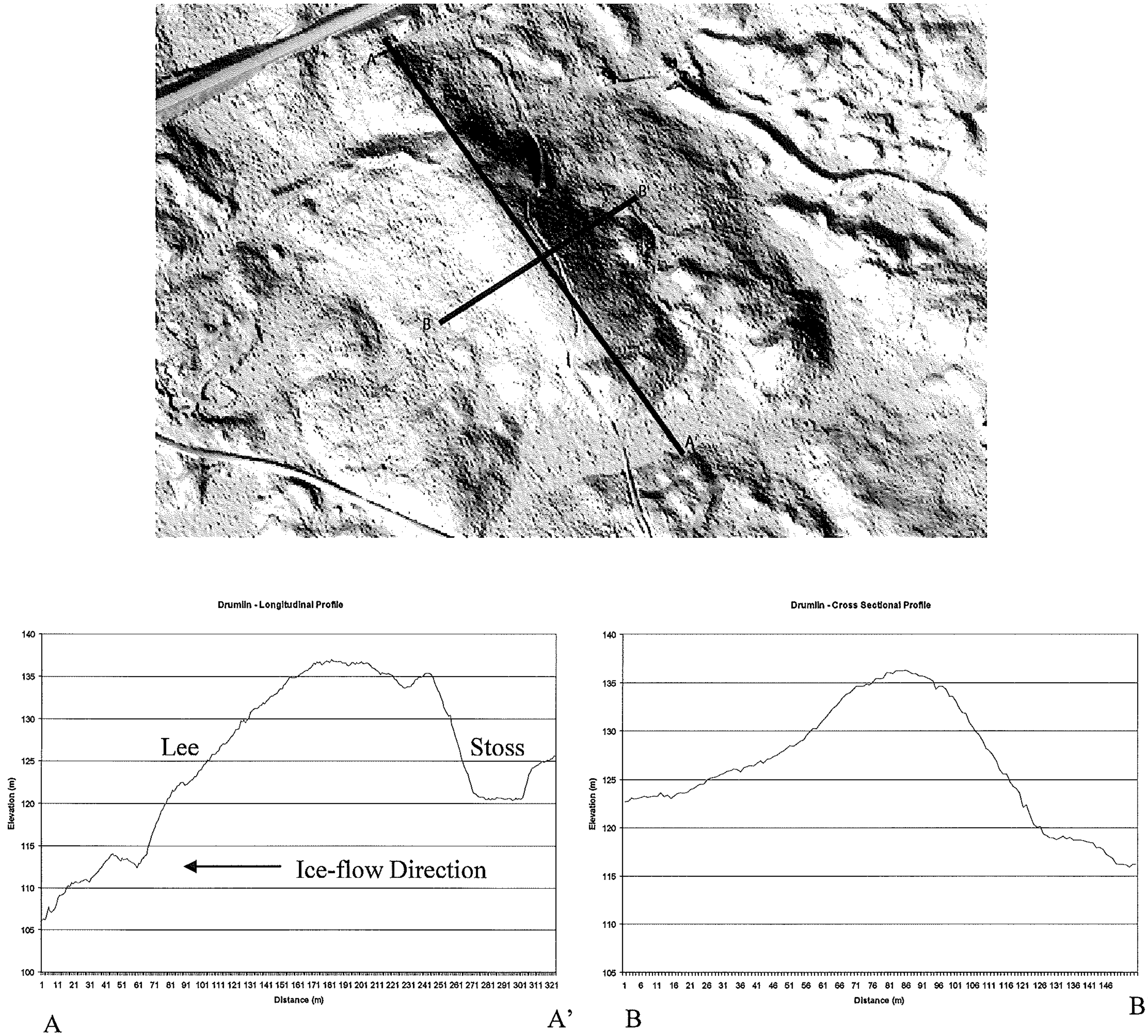



**Figure 4.10 – Drumlin Profile.** This image displays the longitudinal profile (left) and cross-sectional profile (right) of a drumlin located south of Annapolis Royal. The profile allows easy visualization of the drumlin which in turn leads to easy interpretation of ice-flow direction.

# CHAPTER 5 DISCUSSION AND IMPLICATIONS

## 5.1 LiDAR Benefits

The benefits of LiDAR derived DEM's when analyzing surficial and glacial landforms are clearly evident. The ability of LiDAR to penetrate forest canopy and produce 'bald Earth' DEM's allows a much higher resolution inspection and analysis of both large and small scale glacial landforms. This study has shown that LiDAR can produce the resolution required to identify meso-scale landforms that have not been documented in previous mapping campaigns. The benefits of LiDAR imagery over larger areas, for example the entire Annapolis Valley region, would no doubt yield hundreds of newly identified meso-scale landforms, adding valuable information for use in many surficial geological investigations, including verifying with a different dataset the ice dynamics interpretations from striae databases. The ability to generate detailed topographic profiles from the data allows precise orientation measurements to permit determination of ice flow direction during drumlin formation.

Previous studies of the area encountered many difficulties when trying to measure the wave cut terrace. In the field the terrace was hard to identify and trace over large distances (R.R. Stea, personal communication, 2007). The resolution of the LiDAR derived DEM is sufficient to measure this terrace along its entire length in detail. Although limited in this study, it would be advantageous to apply LiDAR data to study the entire wave cut terrace.

## 5.2 Implication for Project Area Ice Dynamics

The discovery of drumlinoid terrain with NNW-oriented long axes in the Annapolis Valley and North Mountain supports previous hypotheses that ice flowed NNW from South Mountain, over the valley and North Mountain into the Bay of Fundy from the Scotian Ice Divide (18 – 15 ka) (Stea and Mott, 1998). Orientations of the longitudinal axis of drumlinoids (Fig. 5.0) are consistent across the North Mountain cuesta. The fact that ice flowed transversely across the Annapolis Valley with little impedance (although there is a slight southward deflection indicated on North Mountain) suggests that the ice would have had to be relatively thick at the time of flow, much thicker then the relief of the North Mountain cuesta (265 m). The slight deflection in flow direction on North Mountain also supports the hypothesis that ice from the Scotian Ice Divide converged with southward flowing ice from ice centers over New Brunswick into the Bay of Fundy, where a more westward combined flow is proposed.

The number and wide spread distribution of the drumlinoids also supports the hypotheses that drumlins and drumlinoids are formed by ice pressure and flow, rather then large volumes of melt water (Shaw, 2002), a source of continuing debate. The volume of water needed to create the landforms across the entire study area would have had to be phenomenal and is not realistic considering that the drumlins have uniform orientations on the mountain tops and in the valley bottom.

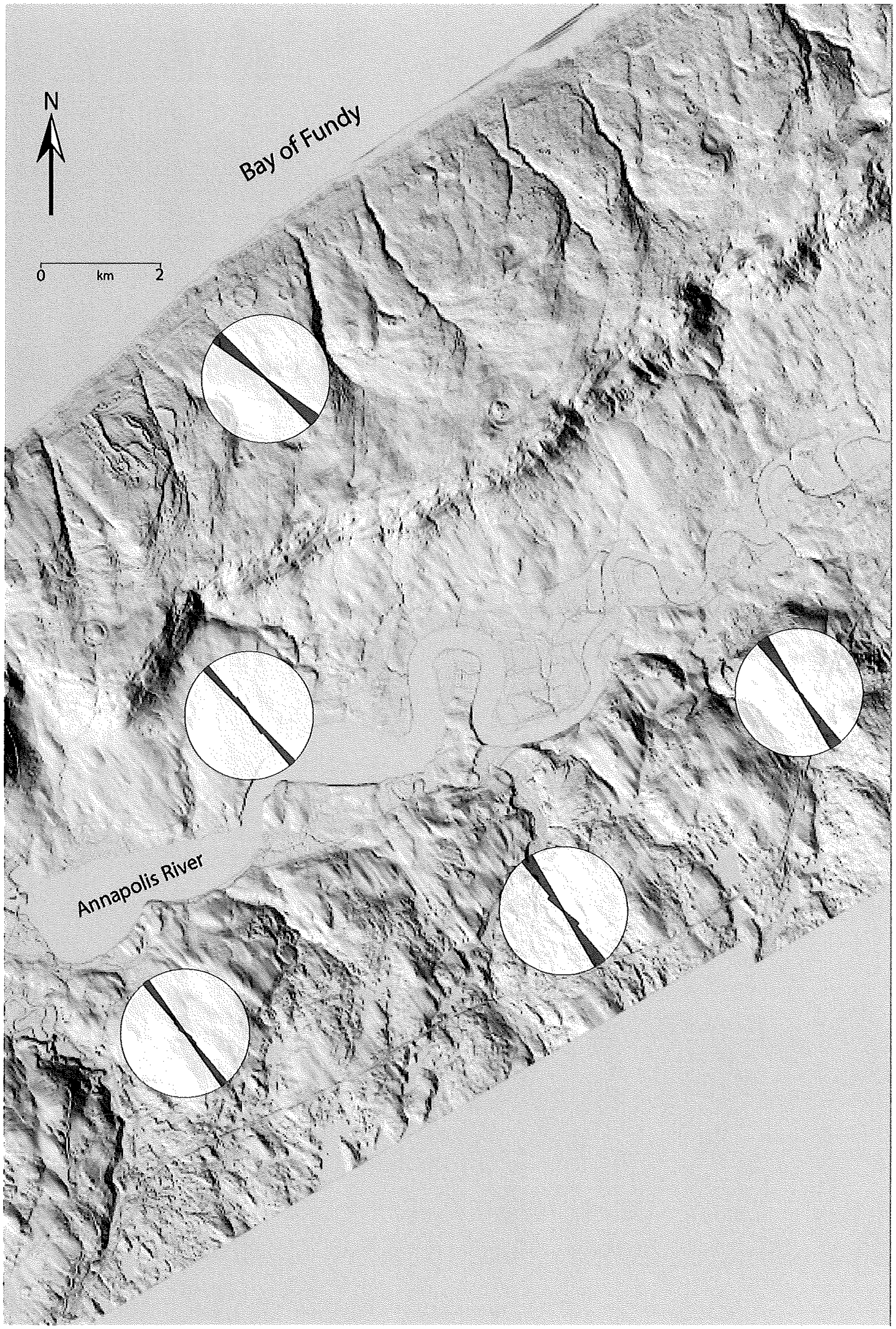



**Figure 5.0 – Drumlinoid Orientations.** Symmetric rose diagrams representing measured orientations of the long axis of drumlinoids found at various localities. Note a slight change in orientation of landforms on North Mountain (northernmost rose diagram). **Image shaded from 225°, light source azimuth 45°, vertical exaggeration 5x.*

## 5.3 LiDAR as an Exploration Tool

Locating new esker systems, which are also a valuable source of high-quality aggregate for the construction industry, is very important because of limited known reserves that are currently accessible. Current methods of aggregate exploration include published Surficial Geology Maps, aerial photography and local knowledge. In this case, LiDAR reveals its value as a tool for both academic research and resource exploration in finding previously unidentified and potential economic deposits of aggregate.

The newly identified esker system (Fig. 4.1) is similar to other deposits being exploited for fine aggregate in Nova Scotia. Volume and tonnage calculations were completed based on measurements taken from each esker to determine the aggregate resource (Table 5.0). In this single esker system there is an estimated 750 x $10^3$ T of potential aggregate. Many other factors, including grain size, grain shape, amount of clay particles and proximity to market influence weather a deposit is economically viable, but the LiDAR data allows companies to focus field exploration and drilling on promising targets without drilling into unknown landforms. If, for example, all of the estimated sand and gravel in the esker system were construction grade aggregate and could be sold to local markets for an average price of $6.00/T, the deposit could potentially hold $4.5 million worth of material.

**Table 5.0 Aggregate Resource Estimate**

| Length (m) | Avg. Height (m) | Avg. Width (m) | Volume ($m^3$) | Tonnage (T) |
|---|---|---|---|---|
| 807 | 10 | 50 | 201750 | 262275 |
| 282.6 | 6 | 25 | 21195 | 27553.5 |
| 581.7 | 6 | 40 | 69804 | 90745.2 |
| 678.4 | 10 | 45 | 152640 | 198432 |
| 651 | 9 | 45 | 131827.5 | 171375.75 |
| | | **Total** | **577 x $10^3$** | **750 x $10^3$** |

## 5.4 Morphosequence Mapping

The morphosequence concept has no relation to time other then the relative location of sequences. In the study area, the oldest glacial landforms created were the drumlins and drumlinoids, formed by molding by ice pressure and flow from the Scotian Ice Divide. During glacial retreat and climatic warming (18 – 15 ka) (Stea et al., 1998) perhaps when the ice margin was receding parallel to the present coastline, eskers (Fig. 4.3) were deposited on the shores of the Bay of Fundy by glacial meltwater. During sequential glacier retreat, the esker flank fans (Fig. 4.4) may have formed at the glacial margin by glacial outwash events. Further work is required to understand these flanking fans. While retreating, glacier melt led to rapidly rising sea levels in the area (12-14 ka) (Stea and Mott, 1998) which truncated the previously deposited esker system (Fig. 4.3). Isostatic rebound due to glacial melting was slower then the rising sea levels at the time, probably because there was remnant ice on inland sections, but further adjustment has since left the wave cut terrace at 37 m asl. The esker system identified in the Annapolis Valley overprints drumlinoids and was most likely deposited during the later stages of deglaciation when small ice caps were located over the South Mountain (12.5 – 11 ka) (Stea et al., 1998).

# CHAPTER 6 CONCLUSION

## 6.1 Conclusion

High resolution surficial data supports previous deglaciation hypotheses and improves our overall understanding of landscape evolution and deglaciation for the study area. Future application of LiDAR to surficial geology and mapping campaigns seems necessary to ensure all meso-scale landforms are documented. The ability to analyze large geographical areas remotely with high resolution eliminates much of the guess work involved when interpreting air photos and satellite imagery in areas of tree cover. Much of the eastern United States and Canada have similar topography and physiography to the study area. The application of LiDAR to deglaciation and surficial geomorphology, as described in this paper, can be transferred to other localities without problem. LiDAR data has proven that, even in populated and well-studied areas, there are meso-scale surficial landforms that go undetected with current mapping methods. Provincial scale mapping and analysis was not completed during this study but it would no doubt be a valuable tool for regional deglaciation based on these results from a relatively small study area.

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# APPENDIX A

## Annapolis Valley Surficial Geology Map - Legend

### SURFICIAL GEOLOGY

**QUATERNARY**

**POST-GLACIAL**

O — ***Organic deposits :*** *peat, muck and bog material, from 0.3 to 3 m thick.*

Ca — ***Colluvial deposits :*** *pebble and angular stones; forming talus cones and gravity accumulations at the foot of rock escarpments.*

***MODERN FLUVIAL AND MARINE DEPOSITS :*** *sediments deposited along modern fluvial systems and during their incision into former Quaternary deposits.*

Ap — ***Modern alluvium :*** *sands, gravely sands, gravels, silts and organic debris; from 0.5 to 3 m thick, forming levees, alluvial bars and modern floodplains.*

At — ***Fluvial terraces alluvium :*** *sands, gravely sands, gravels and organic debris; from 0.5 to 10 m thick; forming terraces delinlating stream entrenchment in former Quaternary formations.*

Mi — ***Intertidal sediments :*** *clayey silt and silty clay, located within a sector along the sea side and regularly inundated by tides; when extending behind dykes this unit is no longer subject to daily tidal action.*

**LAST GLACIATION**

***GLACIOLACUSTRINE DEPOSITS :*** *sediments reworked by a short lived proglacial lake located at the edge of the Annapolis Valley and the Minas Basin following a pronounced climatic cooling at the Younger Dryas (Lv.b); sediments deposited in proglacial lakes fed by glacial melwater and blocked between North Mountain and an ice tongue located within the Annapolis Valley (Lb.v).*

Lv.b — ***Littoral and prelittoral sediments :*** *sand, silty sand, normally graded; can contain ripple laminated units; from 0.3 to 2 m thick, sediments reworked along the edge and within a short lived proglacial lake; with few beach ridges and terraces often visible on the surface; the reworked lake sediments can form a thin layer on underlying deposits.*

Lb.v — ***Littoral, prelittoral and deep water sediments :*** *sand, silt, clayey silt, laminated to massive or roughly stratified and well sorted; from 0.3 to 5 m thick, deposited along the edges of proglacial lakes and within them; with beach ridges and terraces often visible on the surface; the lake sediments are generally flat or slightly undulating, perched above modern streams and rills, they can be thin on underlying material (Lb.v/Tb).*

***MARINE DEPOSITS :*** *sediments deposited during land submersion and subsequent emergence; locally fossiliferous, mainly comprising deep water clays and silts with littoral, prelittoral and deltaic sands and gravels; includes locally glaciomarine diamictons and reworked sediments from underlying units. The maximum marine invasion altitude is 20 m in the eastern and 30 m in the western part of the Annapolis Valley.*

Md — ***Deltaic sediments :*** *sand, gravely sand, gravel and coarse gravel, stratified and well sorted; from 1 to 20 m thick; deposited in the western part of the Annapolis Valley by streams flowing in the sea, forming flat surfaces generally marked by abandoned channel terraces.*

Mb.v — ***Littoral, prelittoral and exundation sediments :*** *silt, sandy silt, massive; from 0.5 to 5 m thick; deposited in shallow water during the marine phase and following emergence; surface can be marked by beach ridges and marine terraces; when associated with exundation facies, these sediments are generally forming a thin layer on underlying deposits.*

Ma — ***Deep water sediments :*** *found in the western Annapolis Valley under fluvial terraces alluvium (At/Ma); red brown clayey silts and silty clays, generally massive; may contain some turbidite layers, from 1 m to more than 7 m (in sections) and 20 m (in drill holes) thick; mainly deposited by settling during the marine inundation.*

***GLACIOFLUVIAL DEPOSITS :*** *stratified sediments deposited by meltwater in contact or in proximity of the glacier. Units under the marine limit, within the eastern sector of the Annapolis Valley, have generally been reworked by waves and currents during the marine submergence and following land emergence.*

Go — ***Subaerial proglacial fan sediments :*** *sand, sandy gravel and boulders; from 1 to 50 m (in drill holes) thick; forming benches and fans with flat to undulating surfaces marked by sinuous shallow paleochannels, specifically in the central sector of the Annapolis Valley.*

Gx — ***Ice contact sediments :*** *sand and gravel, boulders, may contain some diamicton layers; up to 30 m thick; forming eskers, kames and morainic accumulations; surface generally hummocky, locally punctuated with kettles and marked by abrupt slopes along eskers sides.*

***GLACIAL DEPOSITS :*** *diamicton, deposited directly by the glacier, with a silty-sandy matrix within North Mountain area and in the bottom of the Annapolis Valley, it becomes sandier over South Mountain granites. From a reddish brown to brown color on North Mountain and in the bottom of the Annapolis Valley, it can change to a pale brown, even becoming grey white over South Mountain.*

Tb — ***Continuous till cover (blanket) :*** *diamicton comprising lodgement and ablation facies; thickness generally over 1.0 m; this unit is mainly located in intermediate to low relief areas but can also be found on the valley floor and sidewalls of the Annapolis Valley.*

Tv — ***Discontinuous till cover (veneer) :*** *diamicton comprising mainly ablation facies less than 0.5 m thick with surfaces generally punctuated by rock outcrops; underlying rock structure may be locally visible on aerial photos. This unit is mainly located on higher relief areas, specifically on North and South Mountain.*

***Composite units :*** *(O/At, Ca/R, At/Ma, Gx/Tb, Lb.v/Tb, Lb.v/Gx and Lb.v/Tb) indicate the nature of the underlying material to the reader.*

### BEDROCK

**PRE-QUATERNARY**

*Rock outcrop and rock with a thin layer of unconsolidated material.*

R — ***Paleozoic and mesozoic rocks :*** *North Mountain cuesta is essentially composed of triassic lava flows, Annapolis Valley has been eroded through triassic shales and friable sandstones and South Mountain is a granitic batholith.*

*Geological boundary (approximate)*
*Gravel or sand pit*
*Quarry*
*Eolian landforms*
*Channeling*
*Ice contact or proglacial channel (direction of flow known, unknown)*
*Terrace*
*Lacustrine limit*
*Marine limit*
*Intermediate marine level*
*Delta*
*Kame*
*Beach ridge*
*Kettle*
*Esker (direction of flow known)*
*Moraine ridge*
*Crag-and-tail*
*Drumlin*
*Glacial fluting (streamlined parallel to glacial flow)*
*Glacial striae (direction of flow known, unknown)*
*Relative chronology of striated surfaces (1 = older movement)*
*Escarpment in unconsolidated material*
*Rock escarpment*
*Glacial cirque and rock escarpment*
*Lineation controlled by the rock structure*
*Isolated rock outcrop*